Recent developments & future tasks in NNLO top quark theory

Alexander Mitov
Theory Division, CERN

Case for NNLO in top-pair production

Main features:

- ✓ Large NLO QCD corrections
- ✓ Total theory uncertainty at (NLO+resummation)~10%
- ✓ Important for Higgs and bSM physics (M. Peskin: "*BSM Hides beneath Top*")
- ✓ Experimental improvements down to 5% (at LHC)
- ✓ Current LHC data agrees well with SM theory
- ✓ Tevatron data generally agrees too.

The notable exception: Forward-backward asymmetry from Tevatron.

Conclusion: "further scrutiny is needed"

1

Calculation of the total inclusive x-section tT @ NNLO during the last year

- Published qQ → tt +X

  Bärnreuther, Czakon, Mitov `12

- Published all fermionic reactions (qq,qq′,qQ′)

  Czakon, Mitov `12

- Published gq

  Czakon, Mitov `12

- Published gg

  Czakon, Fiedler, Mitov '13

Now the top pair total x-section is known exactly at NNLO in QCD

No approximations of any kind

- First hadron collider calculation at NNLO with more than 2 colored partons.
- First NNLO hadron collider calculation with massive fermions.

P. Bärnreuther et al arXiv:1204.5201

Czakon, Fiedler, Mitov '13

NNLO phenomenology at the Tevatron:

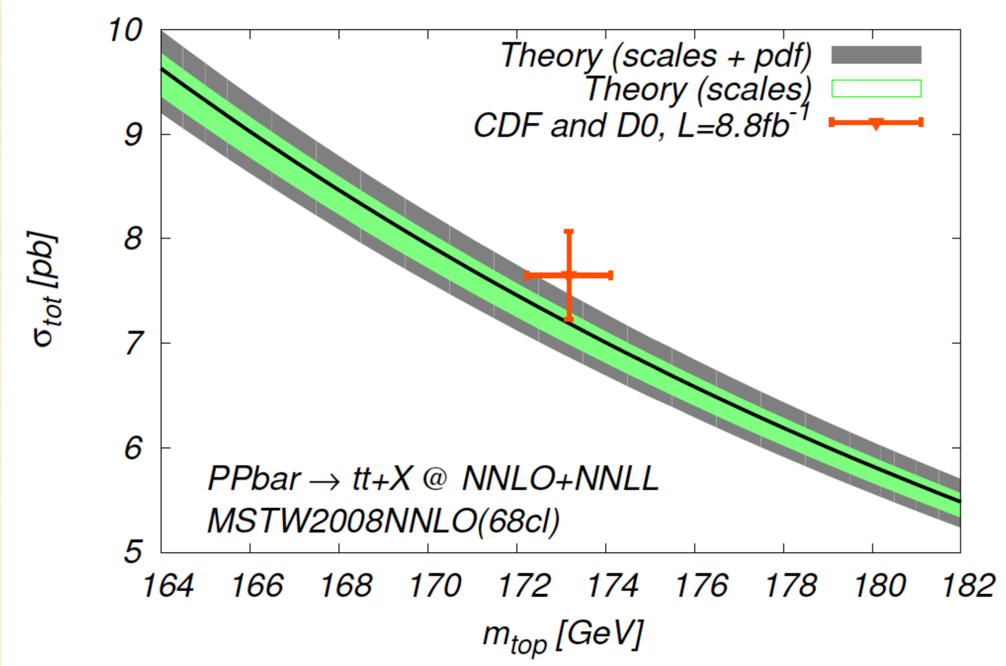
✓ Independent F/R scales
✓ MSTW2008NNLO
✓ mt=173.3

Best prediction at NNLO+NNLL

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

Pure NNLO

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	$+0.259(3.7\%)$ $-0.374(5.3\%)$	$+0.169(2.4\%)$ $-0.121(1.7\%)$
LHC 7 TeV	167.0	$+6.7(4.0\%)$ $-10.7(6.4\%)$	$+4.6(2.8\%)$ $-4.7(2.8\%)$
LHC 8 TeV	239.1	$+9.2(3.9\%)$ $-14.8(6.2\%)$	$+6.1(2.5\%)$ $-6.2(2.6\%)$
LHC 14 TeV	933.0	$+31.8(3.4\%)$ $-51.0(5.5\%)$	$+16.1(1.7\%)$ $-17.6(1.9\%)$



✓ New NNLO gg corrections contribute little, ~ +1.3%, as anticipated.

P. Bärnreuther et al arXiv:1204.5201

✓ Very week dependence on unknown parameters (sub 1%) A, etc.

✓ ~ 50% scales reduction compared to the NLO+NNLL analysis of

Cacciari, Czakon, Mangano, Mitov, Nason '11

$$6.722 \begin{array}{l}+0.238\,(3.5\%)\\-0.410\,(6.1\%)\end{array} [\text{scales}] \begin{array}{l}+0.160\,(2.4\%)\\-0.115\,(1.7\%)\end{array} [\text{PDF}]$$

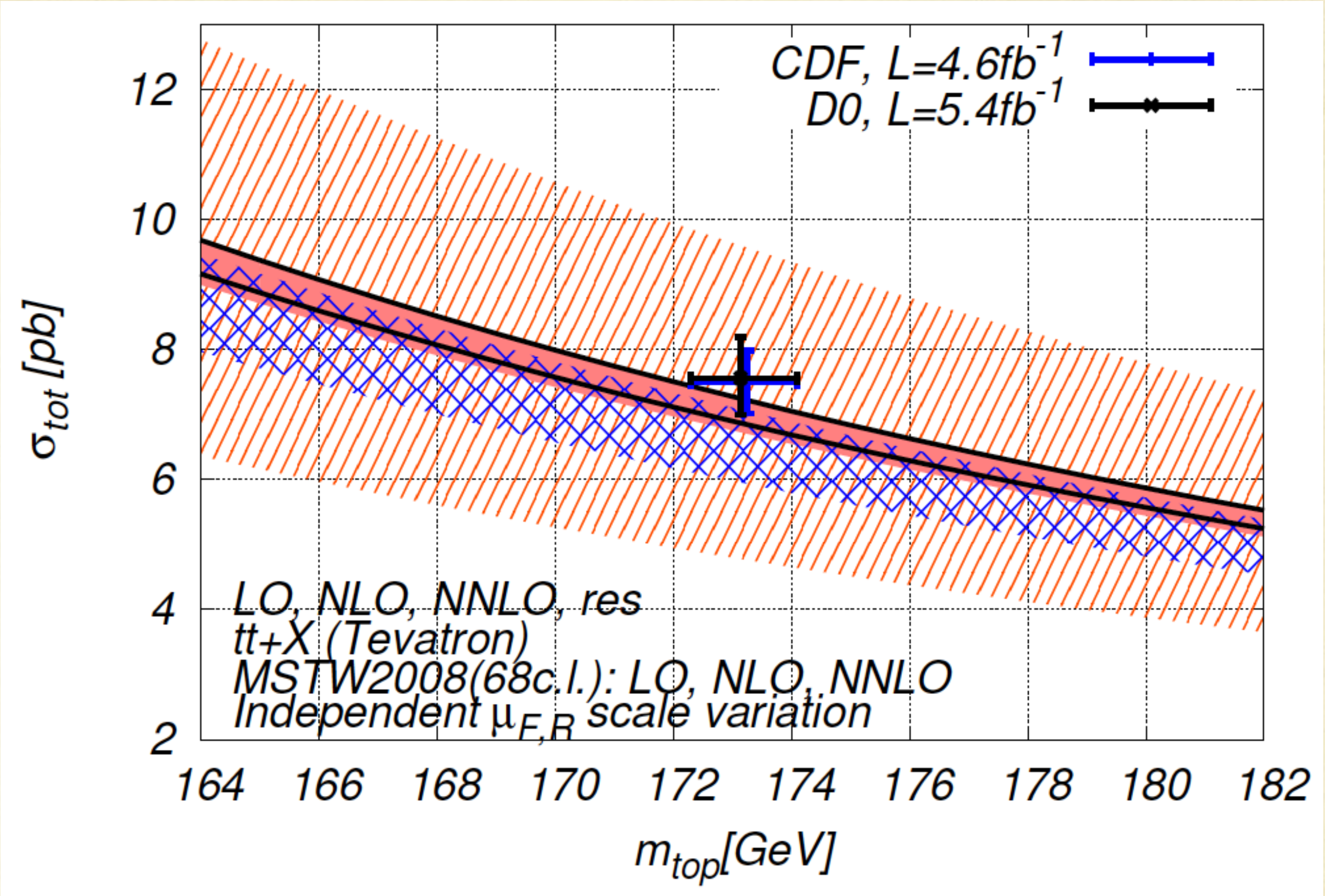
Resumed (approximate NNLO)

3

Good perturbative convergence:

✓ Independent F/R scales
✓ mt=173.3

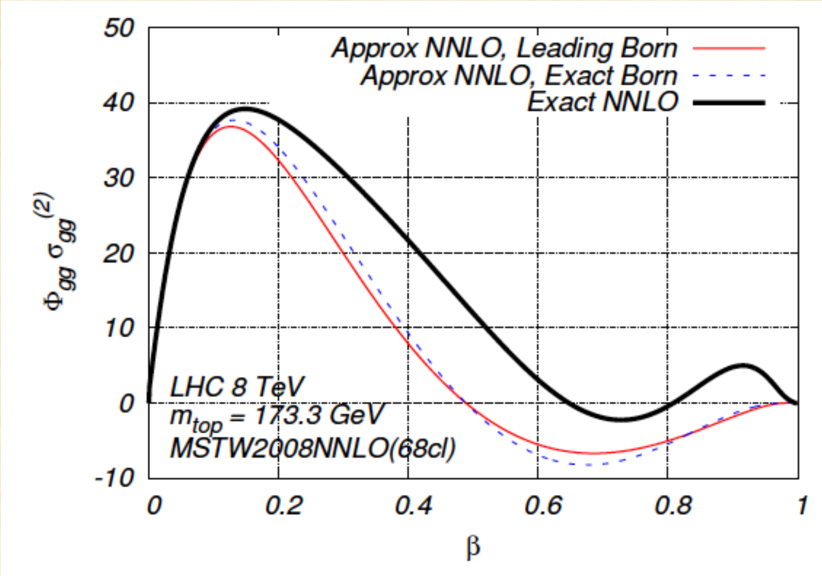
P. Bärnreuther et al arXiv:1204.5201



✓ Good overlap of various orders (LO, NLO, NNLO).
✓ Suggests our (restricted) independent scale variation is good

NNLO phenomenology at the LHC:

Czakon, Fiedler, Mitov '13



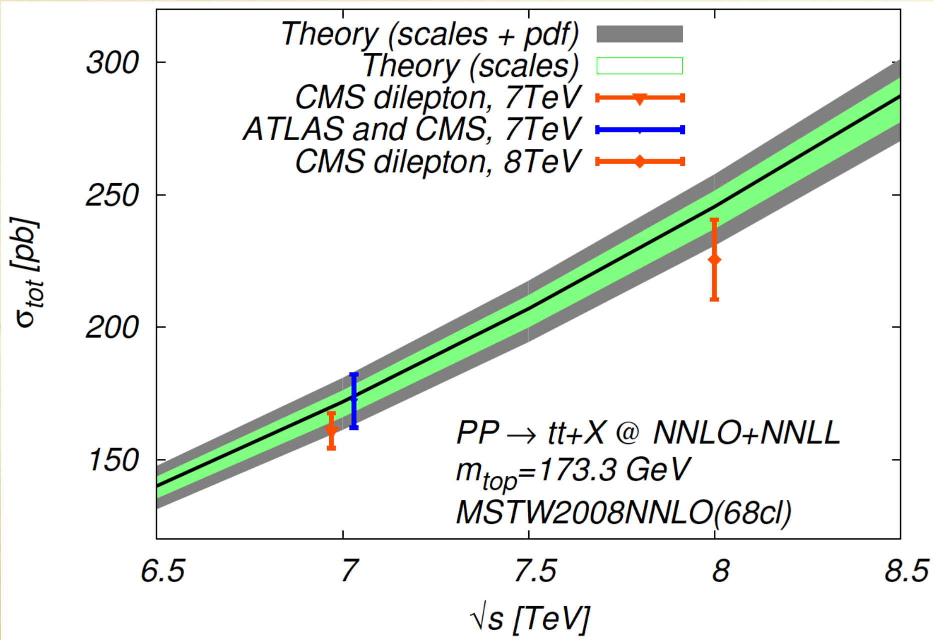
✓ New NNLO corrections from gg-reaction are large: as large as the ones due to the Coulomb-threshold approximation

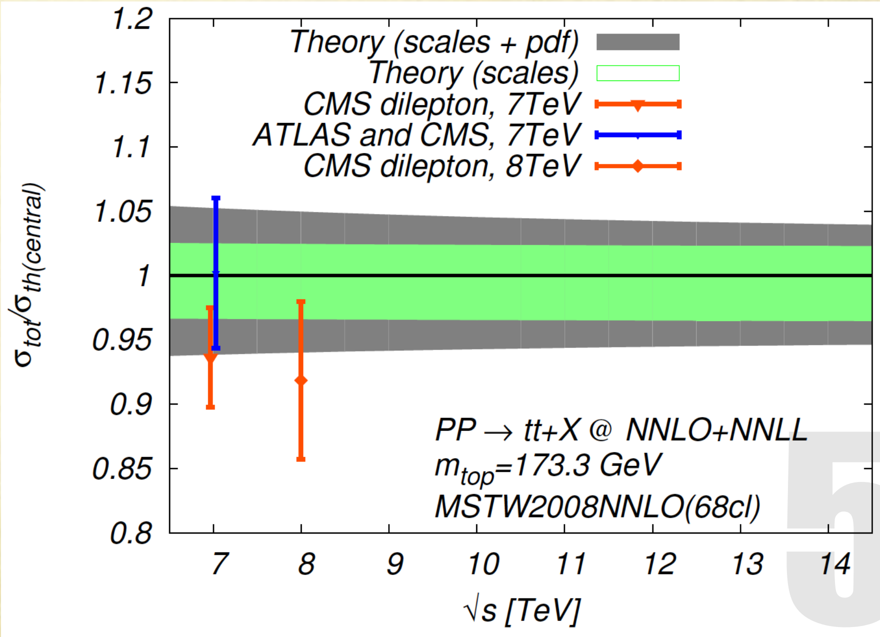
✓ At most 6% scale +pdf uncertainty

✓ Good agreement with LHC measurements

✓ Independent F/R scales
✓ MSTW2008NNLO
✓ mt=173.3

Best prediction at NNLO+NNLL





LHC: general features at NNLO+NNLL

Czakon, Fiedler, Mitov '13

Czakon, Mangano, Mitov, Rojo '13

- ✓ We have reached a point of saturation: uncertainties due to
  - ✓ scales (i.e. missing yet-higher order corrections) ~ 3%
  - ✓ pdf (at 68%cl) ~ 2-3%
  - ✓ alpha_s (parametric) ~ 1.5%
  - ✓ m_top (parametric) ~ 3%

→ All are of similar size!

- ✓ Soft gluon resummation makes a difference: scale uncertainty 5% → 3%

- ✓ The total uncertainty tends to decrease when increasing the LHC energy

LHC: general features at NNLO+NNLL

Czakon, Fiedler, Mitov '13

Czakon, Mangano, Mitov, Rojo '13

The actual numbers for LHC 8 TeV

PDF set	σ_{tt} (pb)	$\delta_{\rm scale}$ (pb)	$\delta_{\rm PDF}$ (pb)	δ_{α_s} (pb)	δ_{m_t} (pb)	$\delta_{\rm tot}$ (pb)
ABM11	198.4	$+4.8$ $(+2.4\%)$ -6.2 (-3.1%)	$+8.5$ $(+4.3\%)$ -8.5 (-4.3%)	$+0.0$ $(+0.0\%)$ -0.0 (-0.0%)	$+6.1$ $(+3.1\%)$ -5.9 (-3.0%)	$+15.3$ $(+7.7\%)$ -16.6 (-8.3%)
CT10	245.9	$+6.2$ $(+2.5\%)$ -8.5 (-3.5%)	$+10.1$ $(+4.1\%)$ -8.2 (-3.3%)	$+4.9$ $(+2.0\%)$ -4.9 (-2.0%)	$+7.4$ $(+3.0\%)$ -7.1 (-2.9%)	$+19.6$ $(+8.0\%)$ -20.4 (-8.3%)
HERA1.5	252.3	$+6.5$ $(+2.6\%)$ -5.7 (-2.3%)	$+5.3$ $(+2.1\%)$ -8.6 (-3.4%)	$+4.0$ $(+1.6\%)$ -4.0 (-1.6%)	$+7.5$ $(+3.0\%)$ -7.3 (-2.9%)	$+16.6$ $(+6.6\%)$ -17.6 (-7.0%)
MSTW08	245.5	$+6.1$ $(+2.5\%)$ -8.3 (-3.4%)	$+6.2$ $(+2.5\%)$ -6.2 (-2.5%)	$+3.9$ $(+1.6\%)$ -3.9 (-1.6%)	$+7.3$ $(+3.0\%)$ -7.1 (-2.9%)	$+16.5$ $(+6.7\%)$ -18.6 (-7.6%)
NNPDF2.3	247.8	$+6.2$ $(+2.5\%)$ -8.6 (-3.5%)	$+6.6$ $(+2.7\%)$ -6.6 (-2.7%)	$+3.7$ $(+1.5\%)$ -3.7 (-1.5%)	$+7.5$ $(+3.0\%)$ -7.2 (-2.9%)	$+16.8$ $(+6.8\%)$ -19.0 (-7.7%)
ATLAS	241.0					$\pm$ 32.0 (13.3%)
CMS	227.0					$\pm$ 15.0 (6.6%)

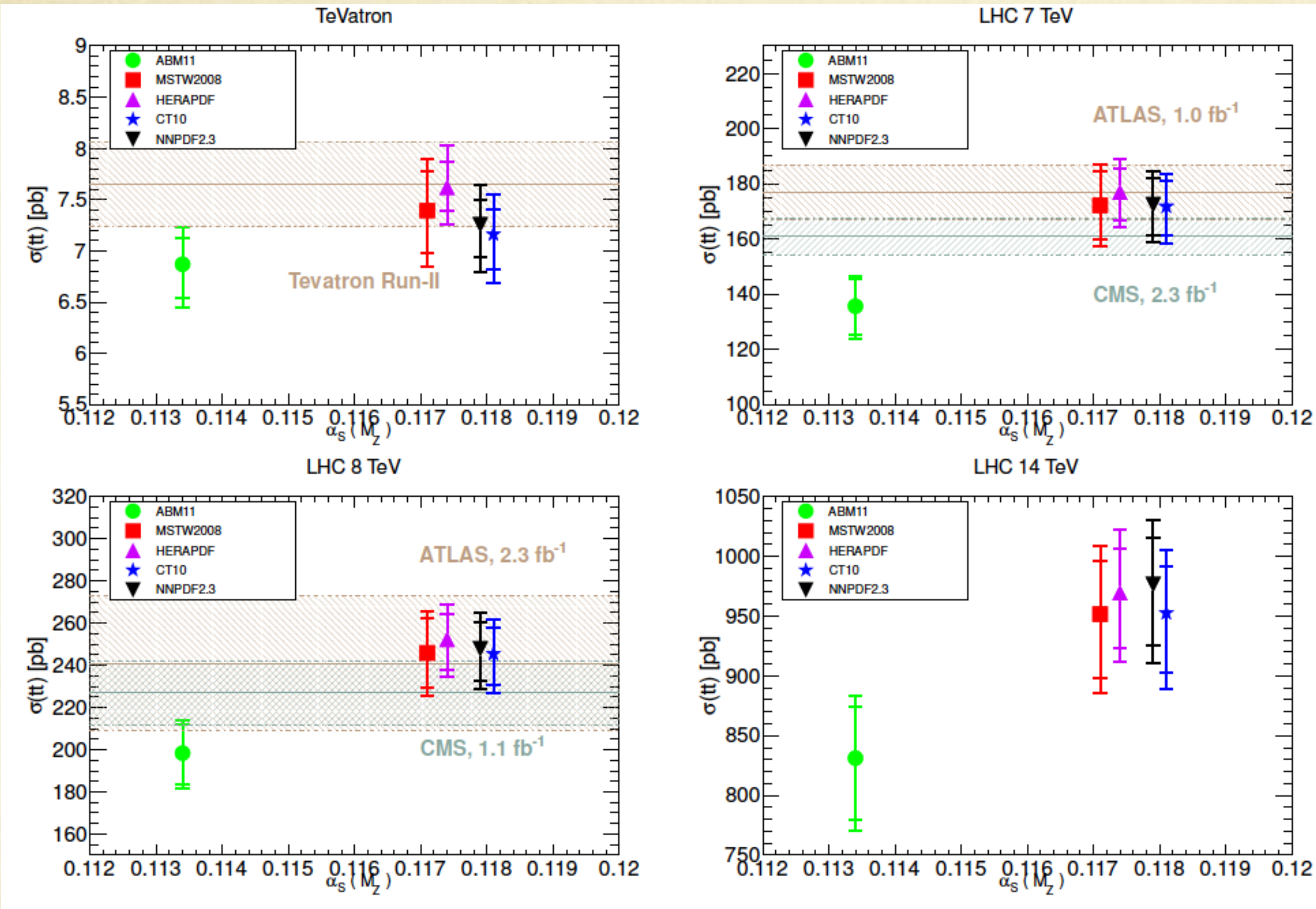
Application to PDF's

Czakon, Mangano, Mitov, Rojo '13

How existing pdf sets fare when compared to existing data?

Most conservative theory uncertainty:

Scales + pdf + as + mtop



Excellent agreement between almost all pdf sets

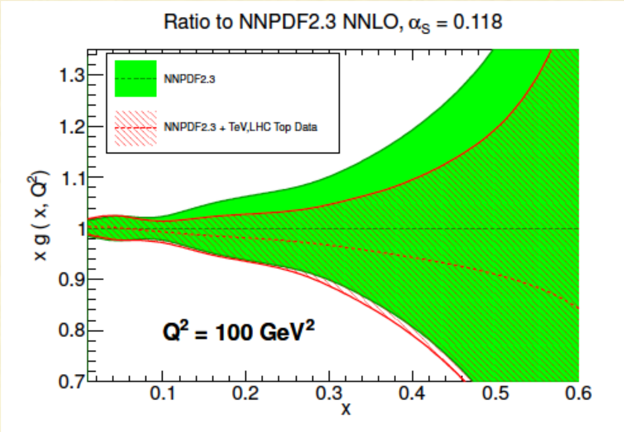
Application to PDF's

✓ tT offers for the first time a direct NNLO handle to the gluon pdf (at hadron colliders)

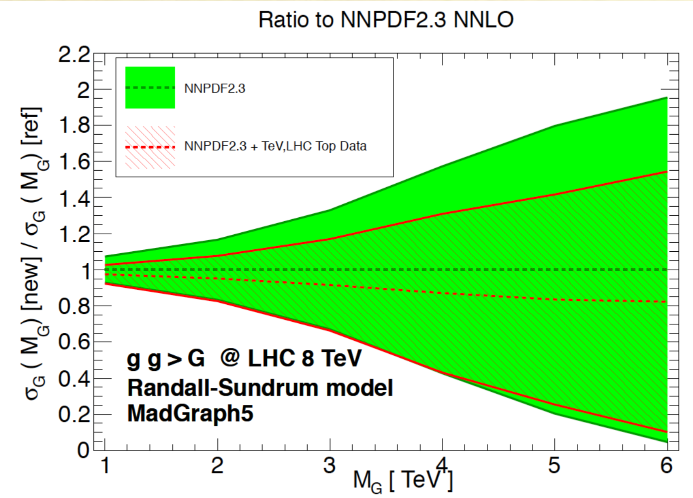
- ✓ implications to many processes at the LHC: Higgs and bSM production at large masses

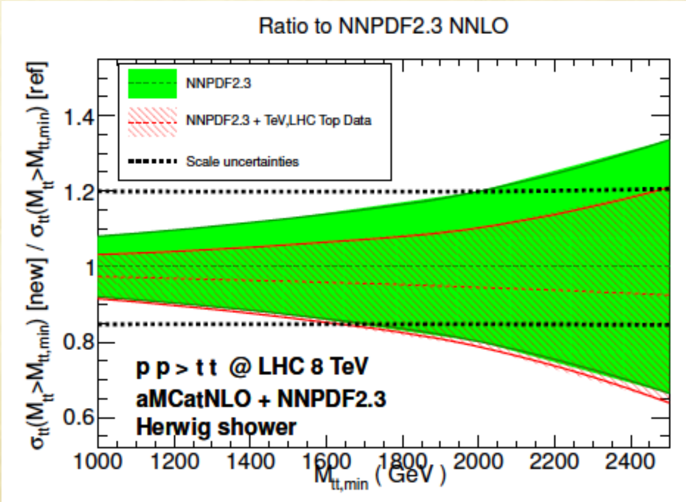
One can use the 5 available (Tevatron/LHC) data-points to improve gluon pdf

"Old" and "new" gluon pdf at large x:



… and PDF uncertainty due to "old" vs. "new" gluon pdf: Czakon, Mangano, Mitov, Rojo '13





Application to bSM searches: stealthy stop

✓ Scenario: stop → top + missing energy

✓ m_stop small: just above the top mass.

✓ Stop mass < 225 GeV is allowed by current data

✓ Usual wisdom: the stop signal hides in the top background

✓ The idea: use the top x-section to derive a bound on the stop mass. Assumptions:

✓ Same experimental signature as pure tops

✓ the measured x-section is a sum of top + stop

✓ Use precise predictions for stop production @ NLO+NLL

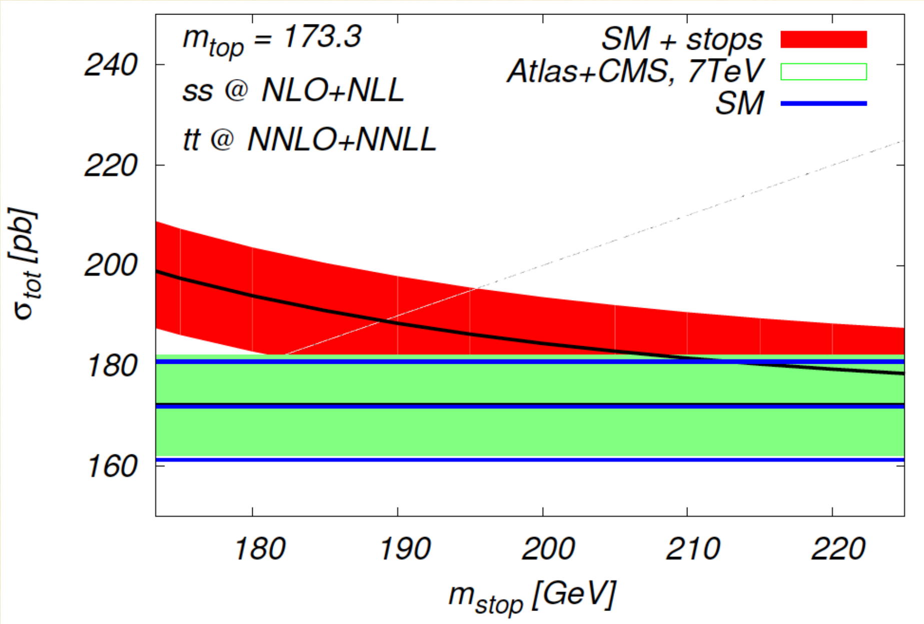
Krämer, Kulesza, van der Leeuw, Mangano, Padhi, Plehn, Portell `12

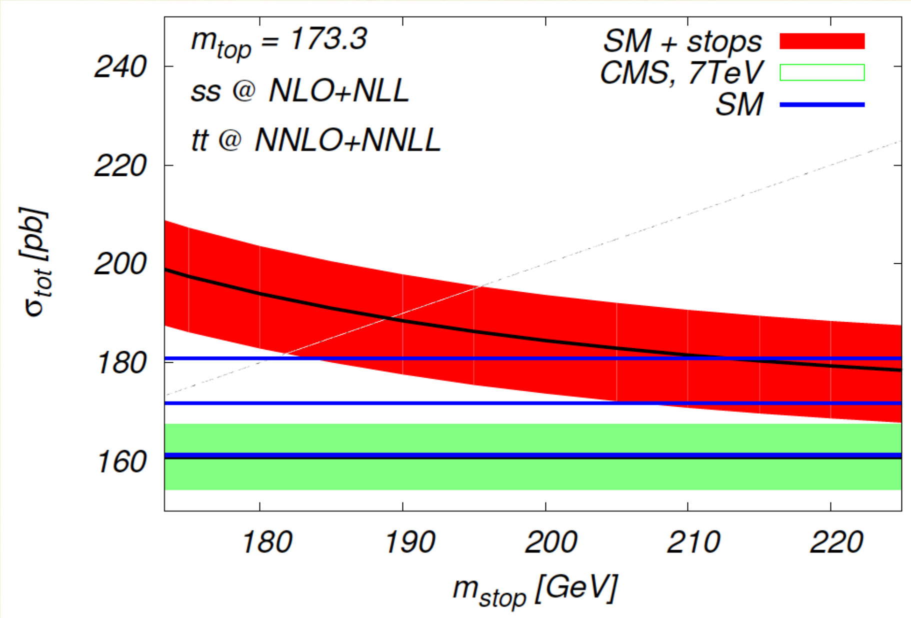
✓ Total theory uncertainty: add SM and SUSY ones in quadrature.

Applications to the bSM searches: stealth stop

✓ Predictions

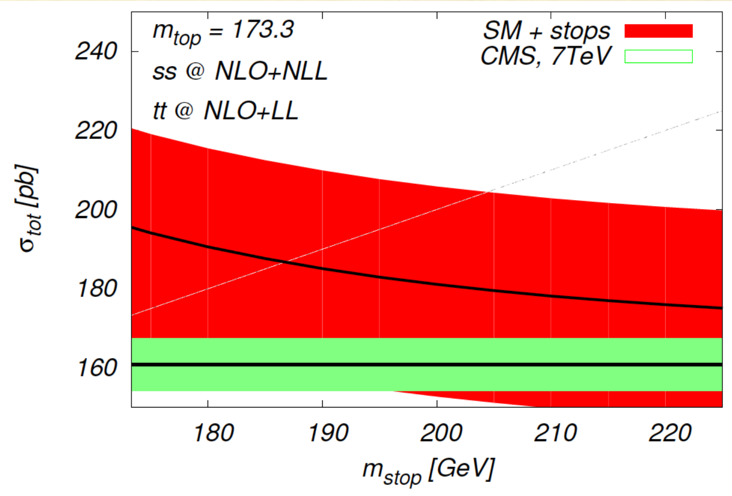
Preliminary





Wonder why limits were not imposed before?

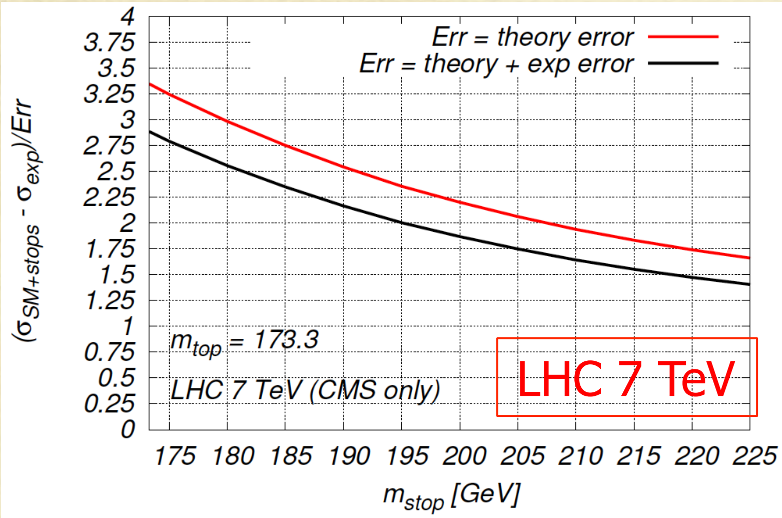
Here is the result with "NLO+shower" accuracy :

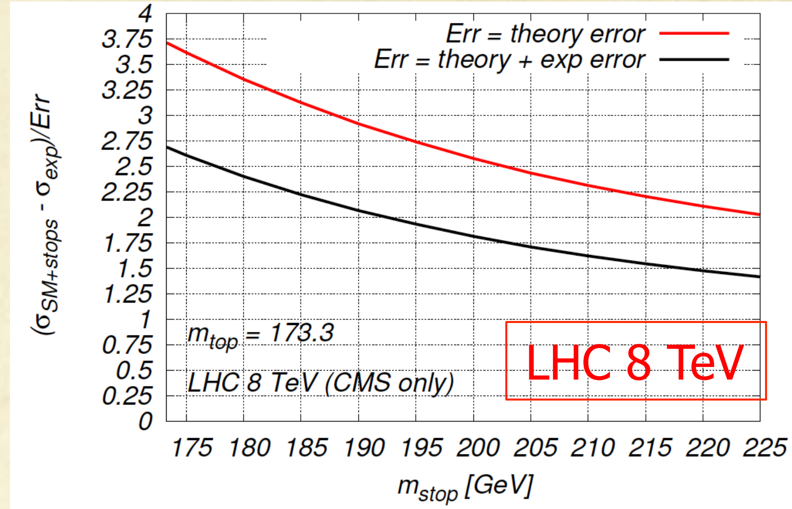


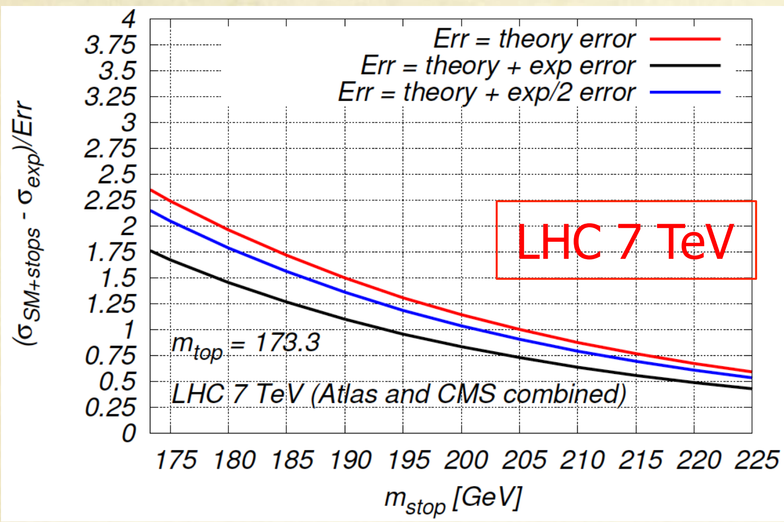
Improved NNLO accuracy makes all the difference

Applications to bSM searches: stealth stop

✓ How strong exclusions can be placed? Preliminary







CMS data allows 2 sigma exclusion for

m_stop < 195 GeV

CMS and Atlas combined data (same as SM) allows 2 sigma exclusion for

m_stop < 177 GeV
(if combined exp error reduced by ½)

Clearly, theory permits exclusion; looking forward to future data improvements!

Currently refining the analysis (with Czakon, Papucci, Ruderman, Weiler)

Summary and Conclusions

- Total x-section for tT production now known in full NNLO
- Small scale uncertainty (2.2% Tevatron, 3% LHC). Similar to uncertainties from pdf, α_S, M_{top}
- Important phenomenology
  - Constrain and improve PDF's
  - Searches for new physics
  - Very high-precision test of SM (given exp is already at 5% !). Good agreement.

Future tasks

- The idea is to compute fully differential top production, including decays (in NWA), at NNLO
- This is complicated and will take time (beyond summer 2013)
- What can be done by then is to compute $O(\alpha_S^4)$ corrections to A_{FB}